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Failure Analysis of a Gas-Nitrided 15-5PH Steel

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 - NASA JSC ES4
 - NASA MSFC EM30
 - NASA KSC NE
 - NASA Engineering & Safety Center (NESC)
 - Boeing
 - Lockheed-Martin
 - ATK
 - Numerous Supportive Subcontractors

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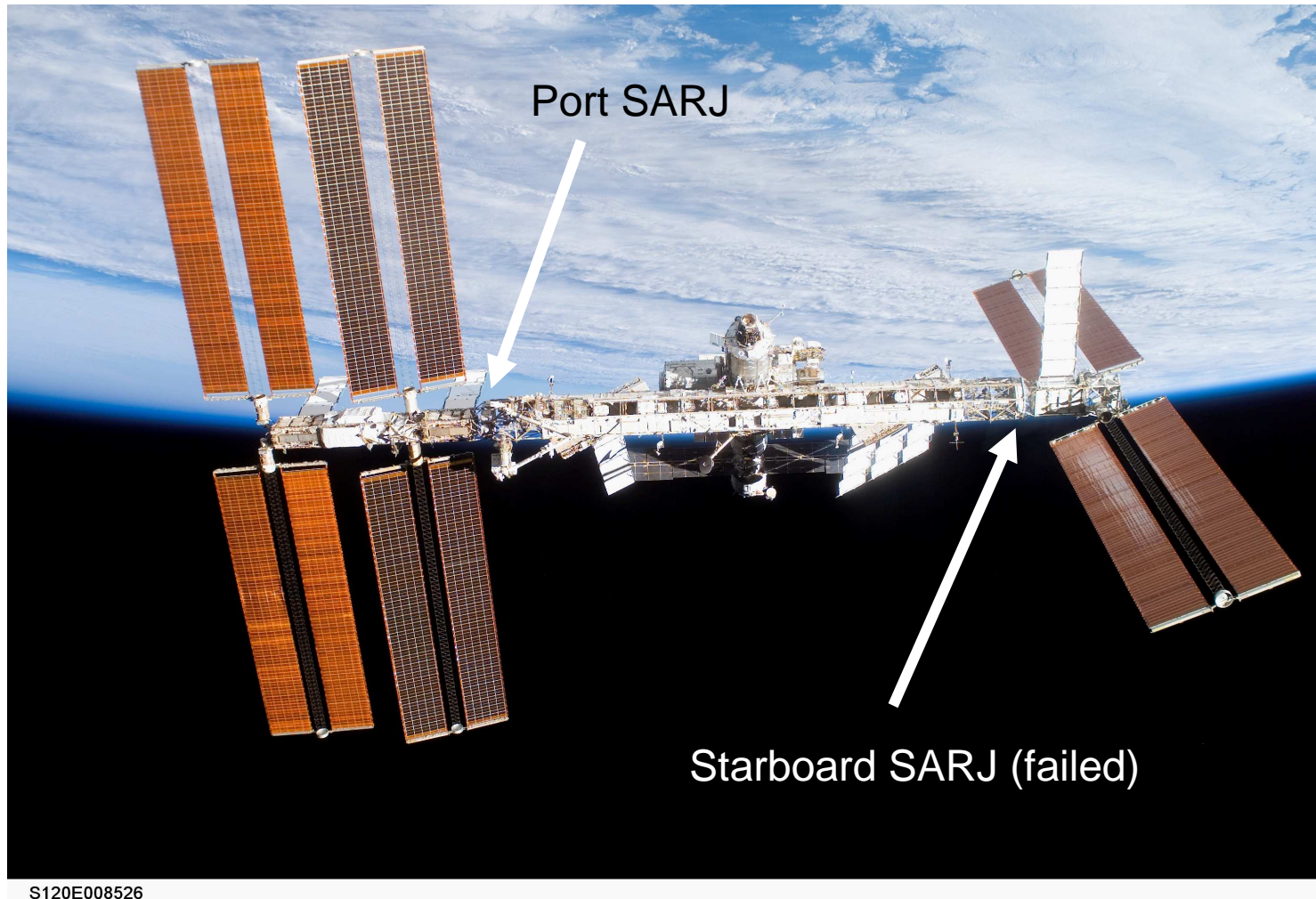
Summary of Presentation

- **Brief Background on the Failure**
 - International Space Station; Solar Alpha Rotary Joint
 - “What do you do when you cannot get at the hardware?”
- **Failure Analysis Approach**
 - Sampling Failed Surface and Microscopy/Metallography
 - Review of All Acceptance Data
 - Sampling of Production Witness Specimens
 - Sampling on Engineering Development and Spare Parts
 - Production of Test Articles for Mechanical Test in an Attempt to Duplicate Flight System Failure
 - Use as high a fidelity as is reasonable
 - Nitrided 15-5PH steel (same steel spec., same heat treatment, same nitriding process and processor).
 - IVD gold coating on 440C (roller simulation with same process and processor)
 - Comparable mechanism kinematics

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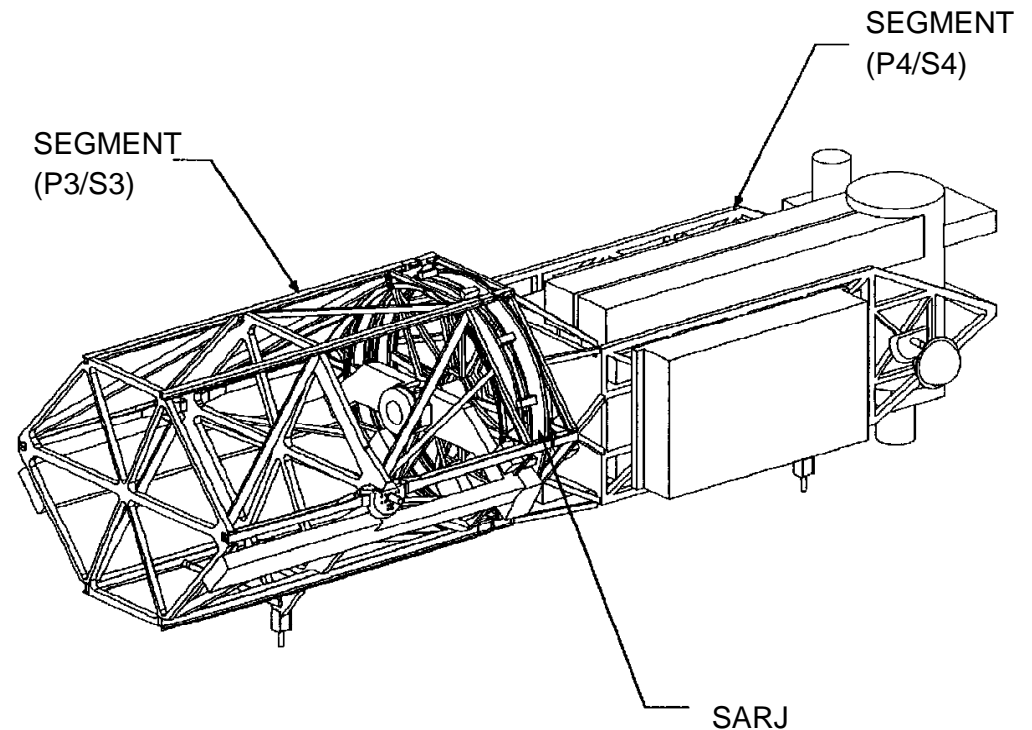
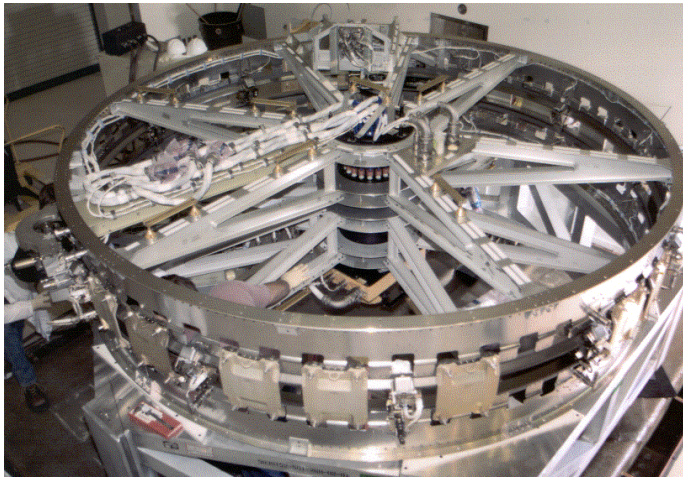
ISS 2007 Configuration: Solar Alpha Rotary Joint (SARJ) Locations

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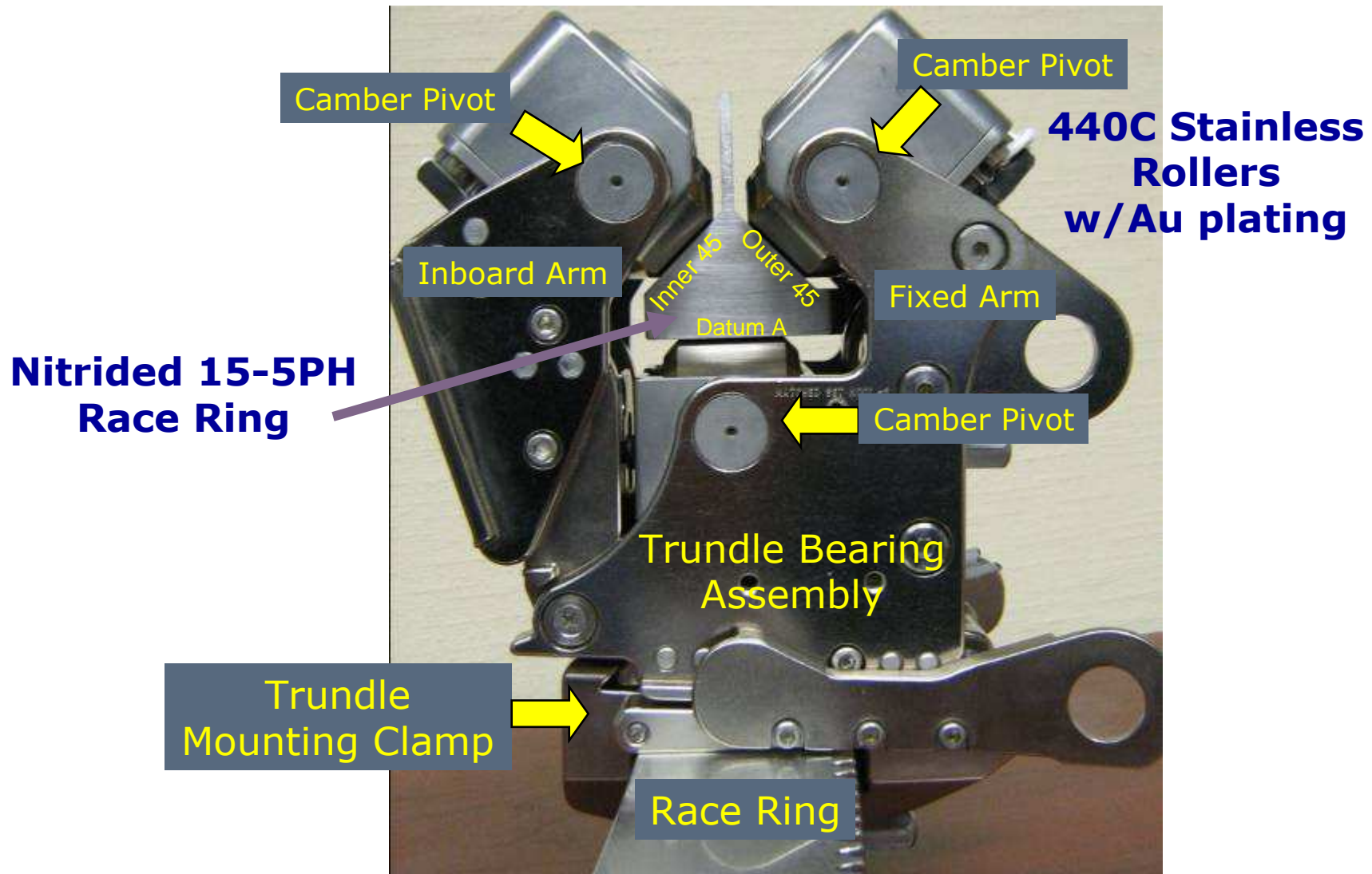
The Solar Alpha Rotary Joint (SARJ) is used to rotate the outboard Solar Array Wings (SAW) and transfer generated power to the ISS pressurized elements



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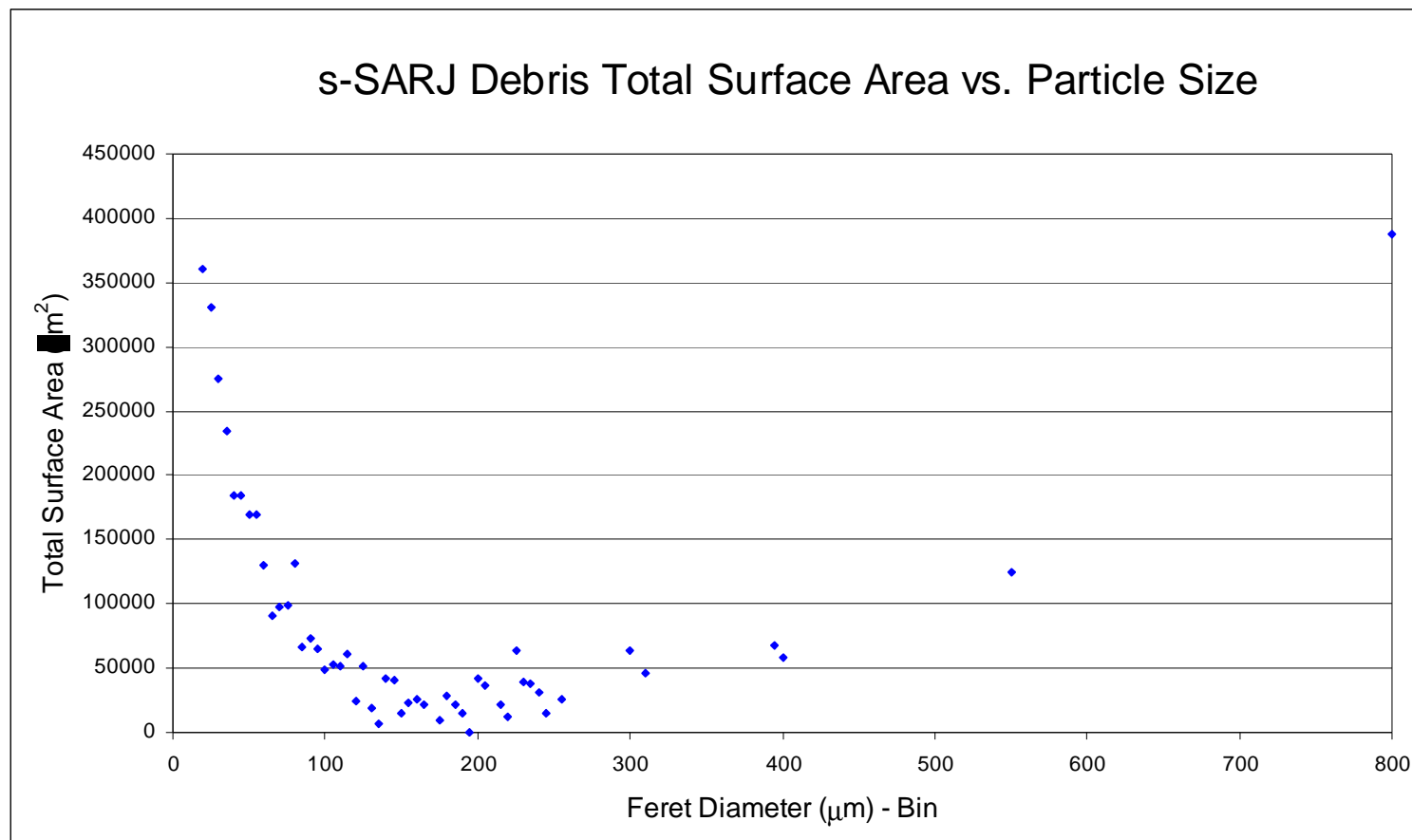
Initial Examination of Starboard SARJ Race Ring Damage

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- **Physical Characteristics of the Failure Debris**
 - **Particle Size Distribution**



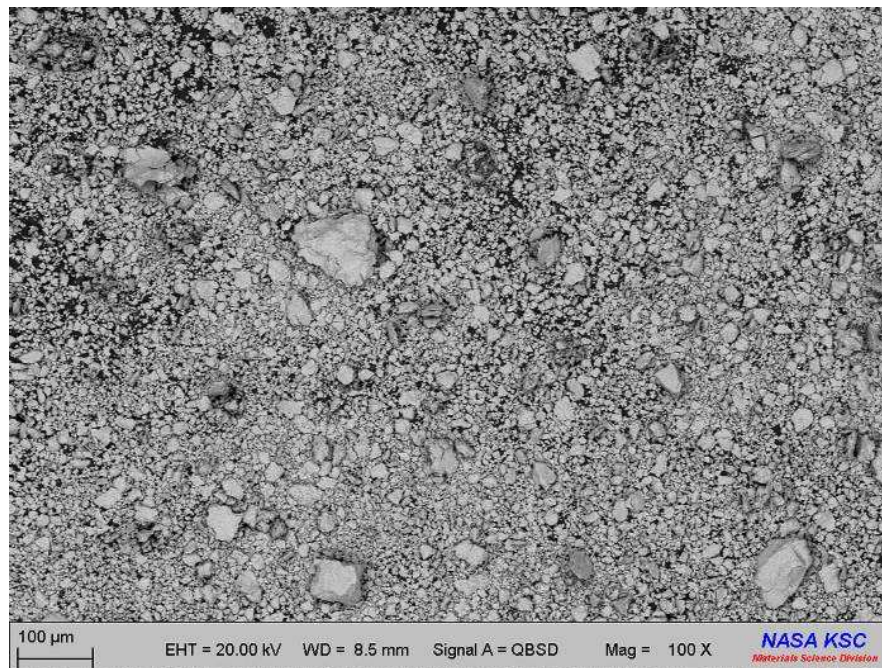
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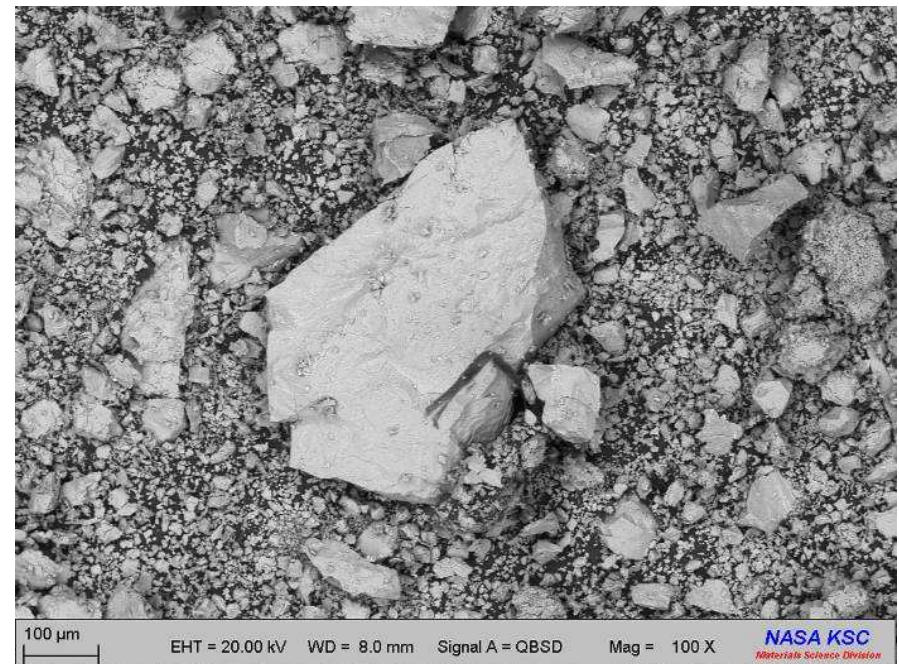
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- **Physical Characteristics of the Failure Debris – Cont.**
 - **Particle Size Distribution – Both views are 100X**

Representative area of
“fine” debris (< 100 μm)



Representative area of all debris;
broad particle size distribution

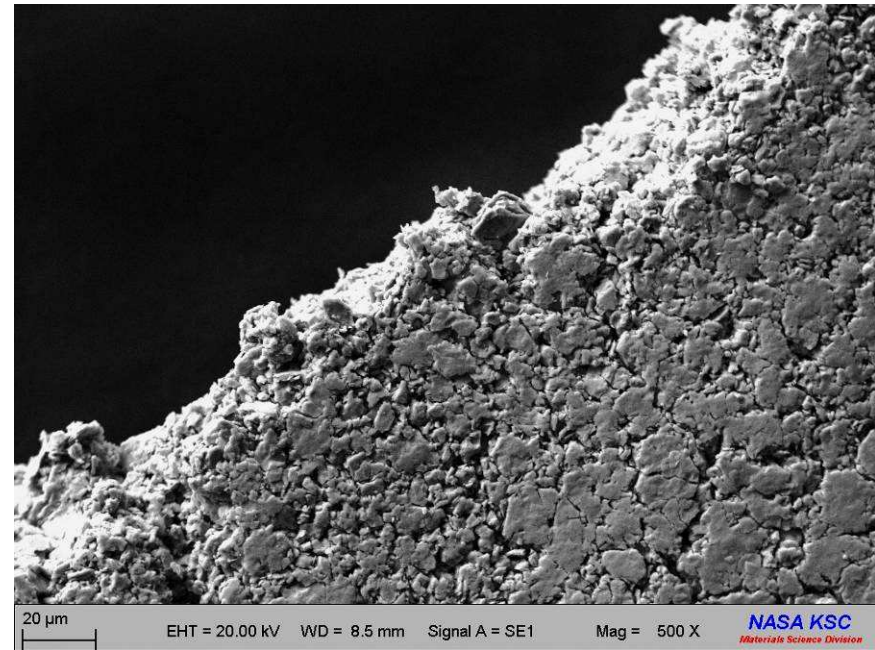
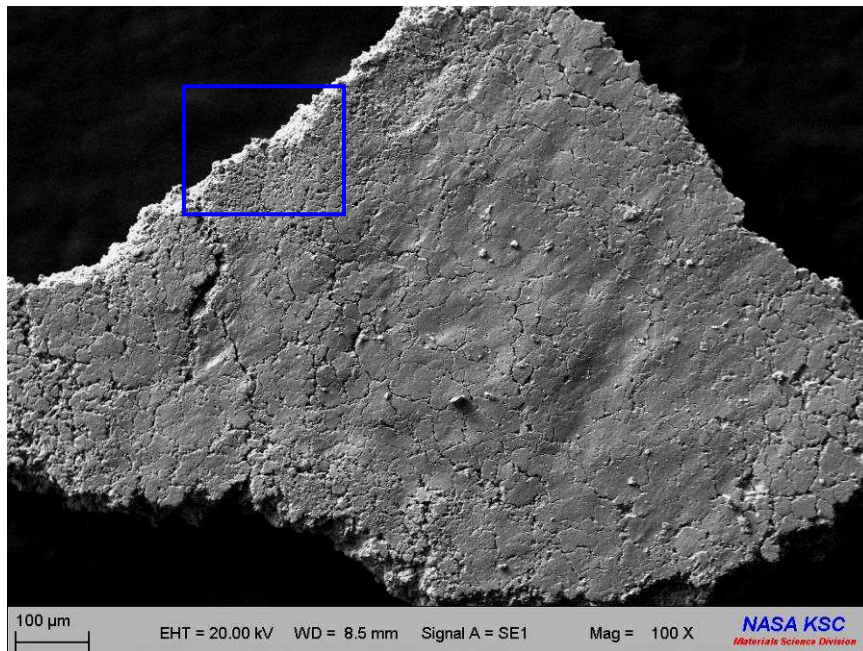


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- **Physical Characteristics of the Failure Debris – Cont.**
 - **Particle Types – Agglomeration Particles**



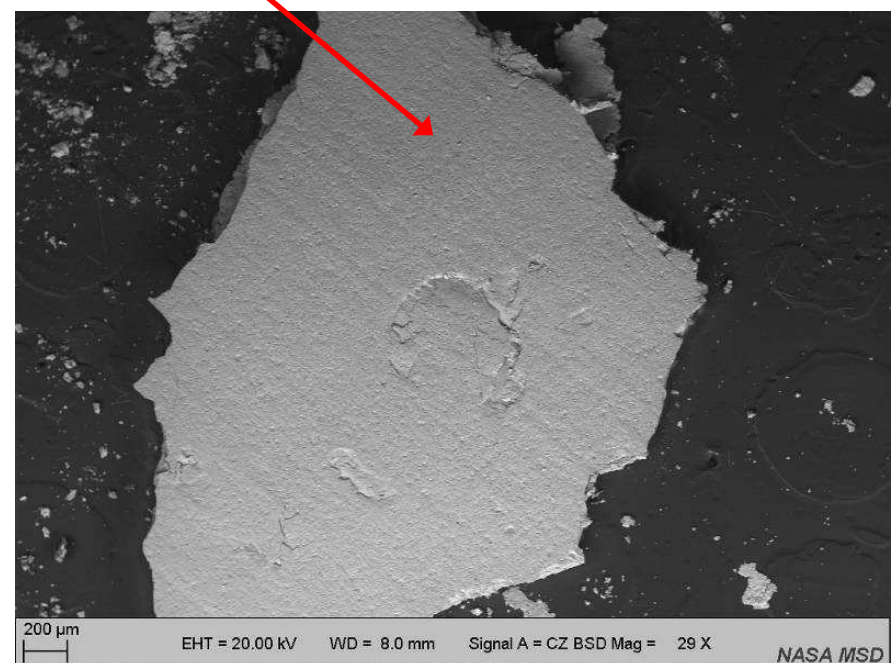
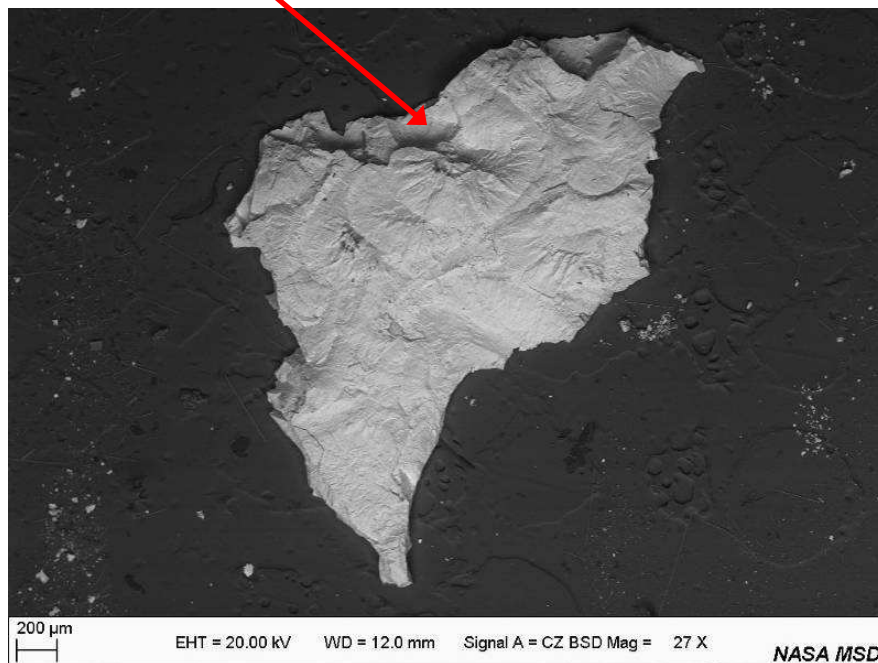
Nitrided 15-5 PH agglomerated fragment from Tape 31 imaged under high vacuum.
Reference magnifications: 100X (left), 500X (right)

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- **Physical Characteristics of the Failure Debris – Cont.**
 - **Particle Types – “Large Chip” Particles**
 - Original surface typically visible on one side (right photo)
 - Low cycle subsurface fractures on the other (left photo)
 - Thickness typically at or near nitride layer thickness

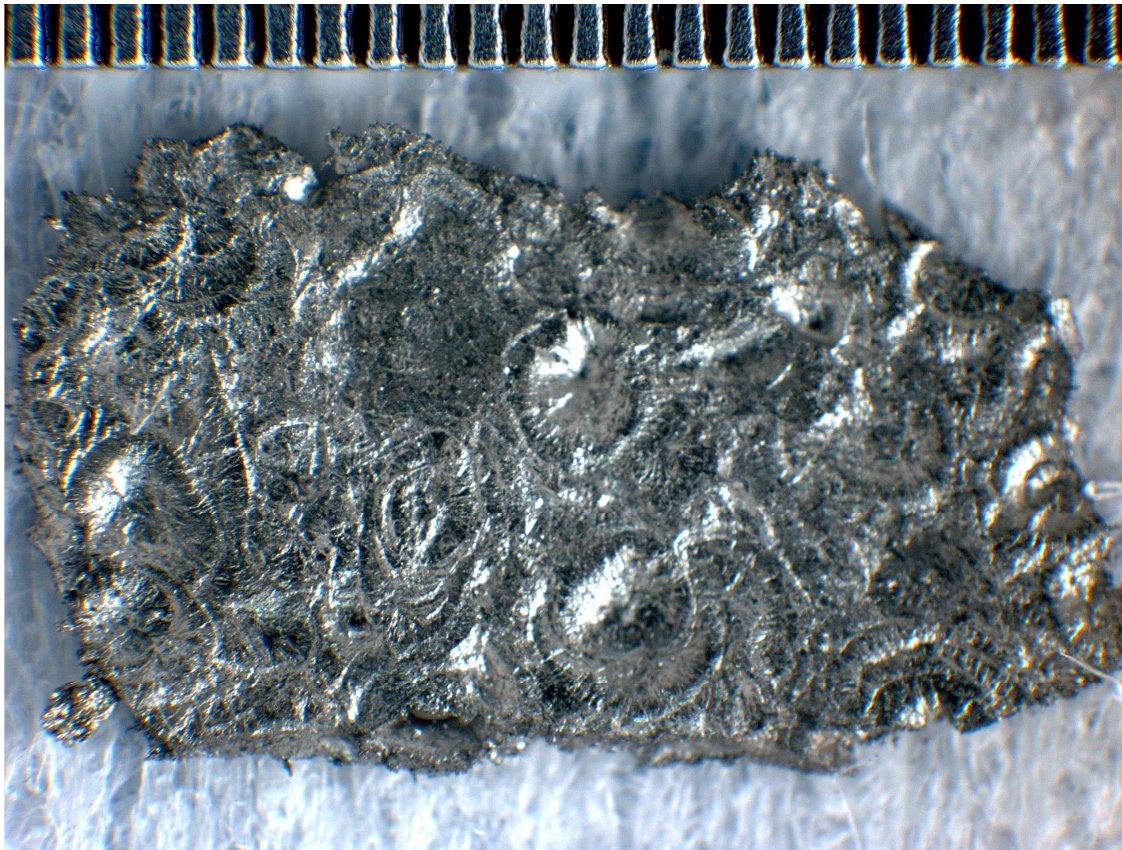


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- **Physical Characteristics of the Failure Debris – Cont.**
 - **Fracture Surfaces on “Chip” Particles – Continued**



- Largest particle located was ~3mm x ~5 mm.
- Particle thickness was about 150-170 μm , essentially equal to the nitride layer thickness.
- Numerous subsurface fracture initiation sites were observed, indicating a low-cycle fracture phenomenon took place.

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- **Physical Characteristics of the Failure Debris – Cont.**
 - **“Chip” Particles In Cross-Section**



Typical large “chip” cross section showing:

- Maximum thickness essentially equivalent to nitride layer thickness, indicating failure is occurring near the case/core interface;
- Evidence of residual “white layer”, in excess of the 8 μm maximum required.
- Fracture lines are transgranular, showing no preference for the intergranular networking observed near the surface.

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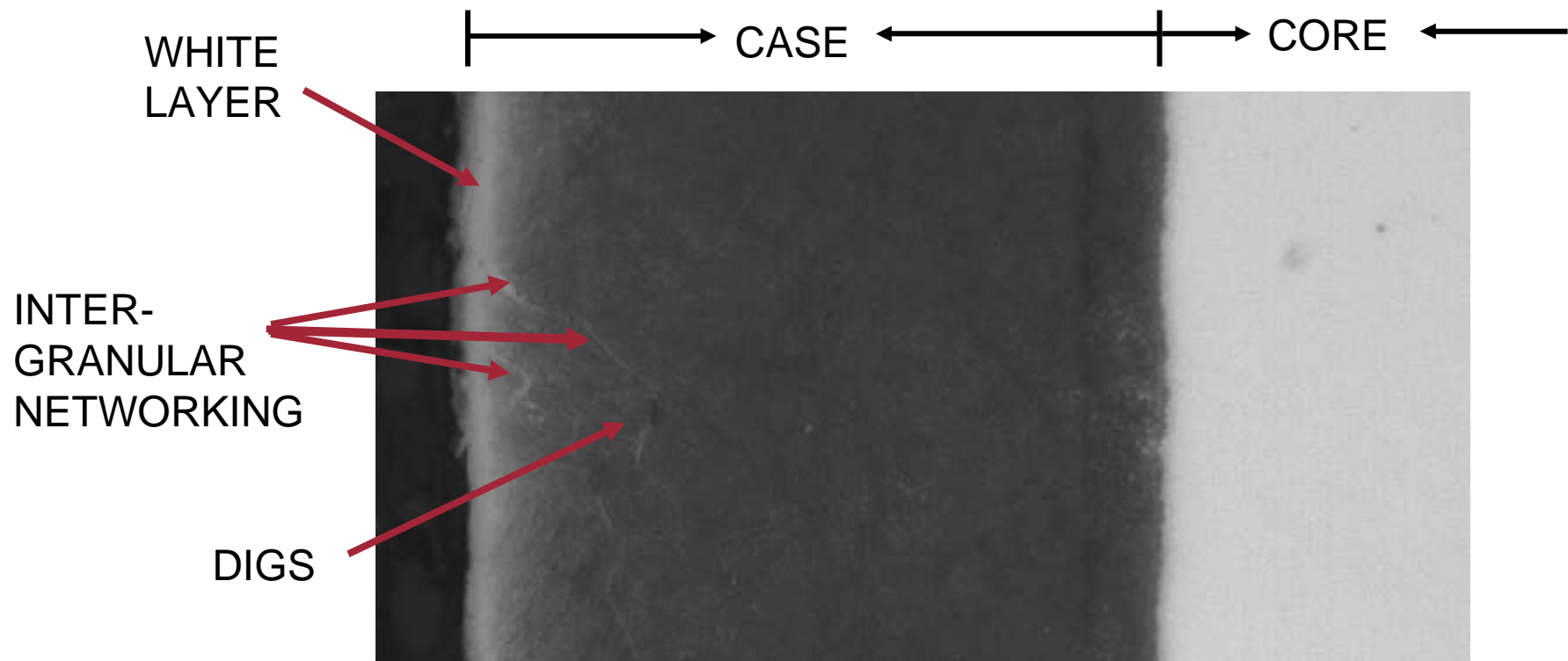
- **We observed Discontinuous Intergranular Separations (DIGS) in the nitride layer on our 15-5PH steel**
 - Once the decision was made to surface harden the SARJ race rings, the gas nitriding process was geared toward producing a nitride layer of 150 μm minimum in a relatively short time (36 hours).
 - Principal means used to accomplish these goals was with the use of an activator.
 - Our team's theory is that nitrogen supersaturation of the 15-5PH steel surface occurred, which on cooling led to separations forming along some grain boundaries in the outer 50 μm of the surface.
 - Differences in DIGS concentration appears to be related to the amount of activator used during the heat treatment.
 - Thirty percent more activator was used on the Starboard SARJ race ring than was used for the Port race ring.

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- **How did we miss the DIGS originally?**
 - They were right in front of us, but not recognized as an issue.
 - Micrograph below is from original test coupon inspection.

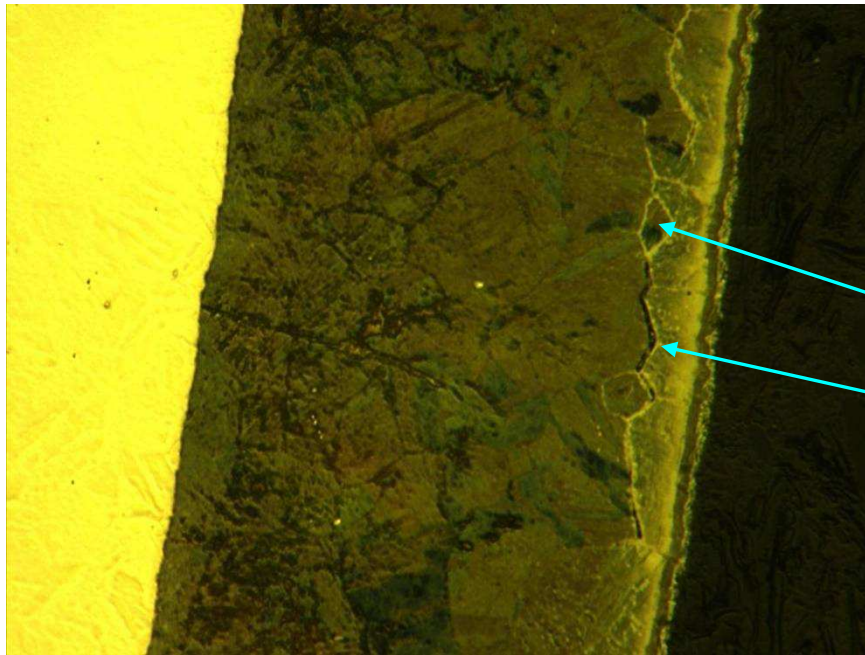
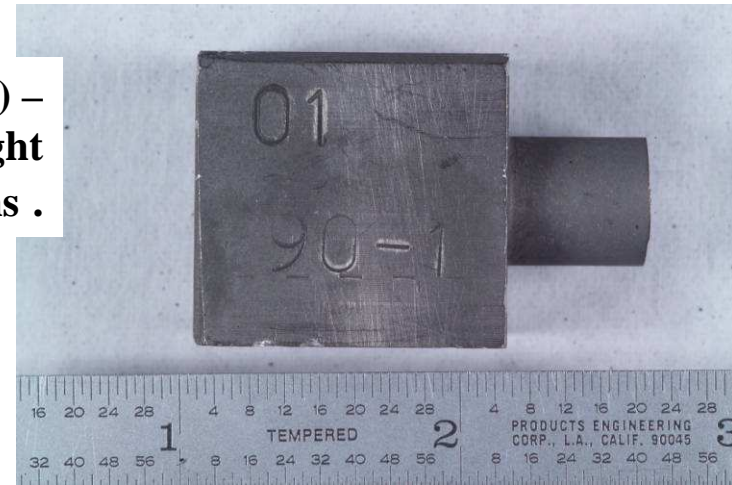


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**Nitride Control Coupon (NCC) –
Nitrided in same furnace as the flight
SARJ race ring, at fixed locations .**



**Metallurgical Evaluation of SARJ Race Ring
S/N 4
Sample Coupon (Polished, Etched and View
@1000X)**

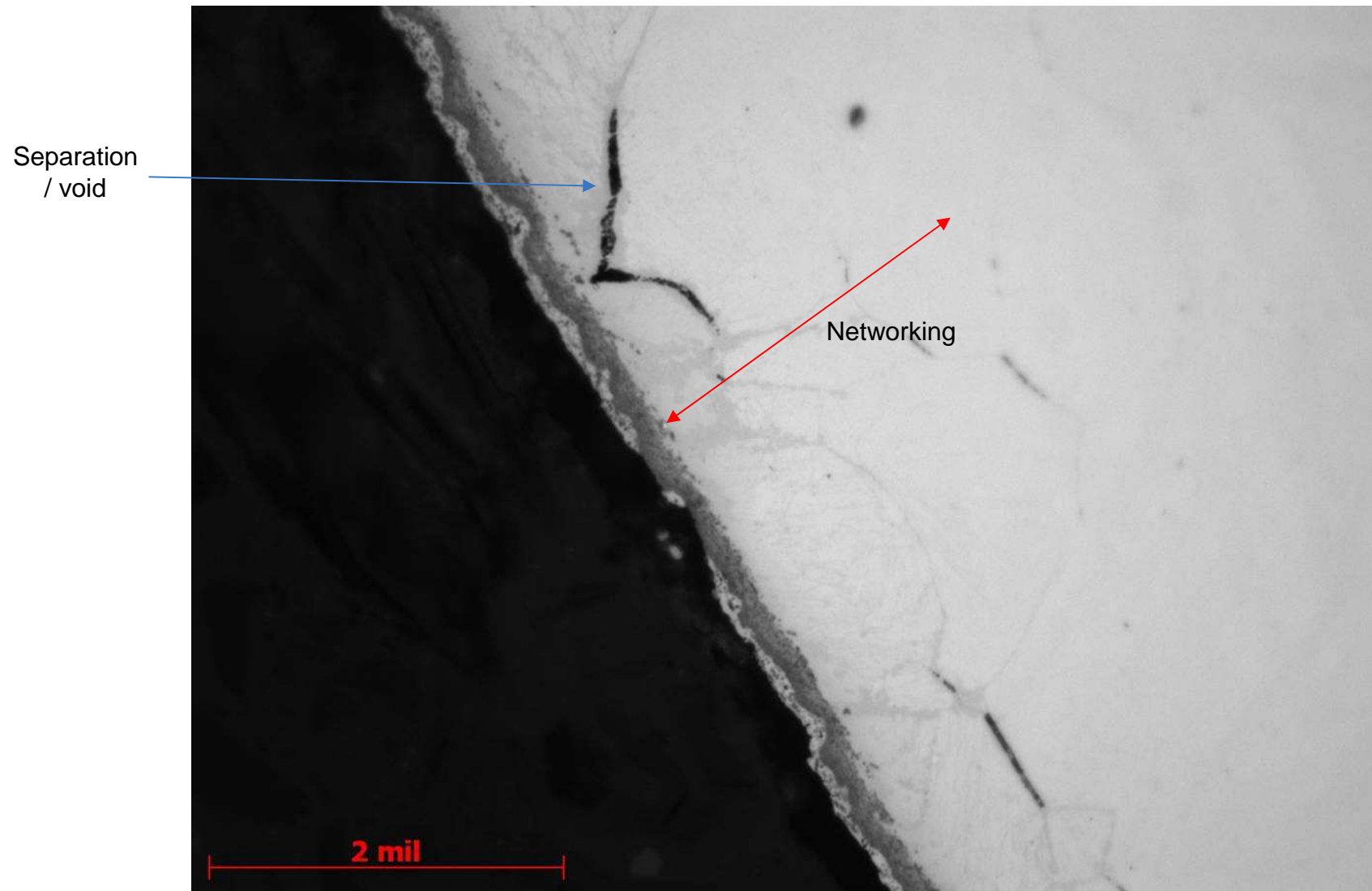
Networking

Intergranular separations
(appear like cracks)

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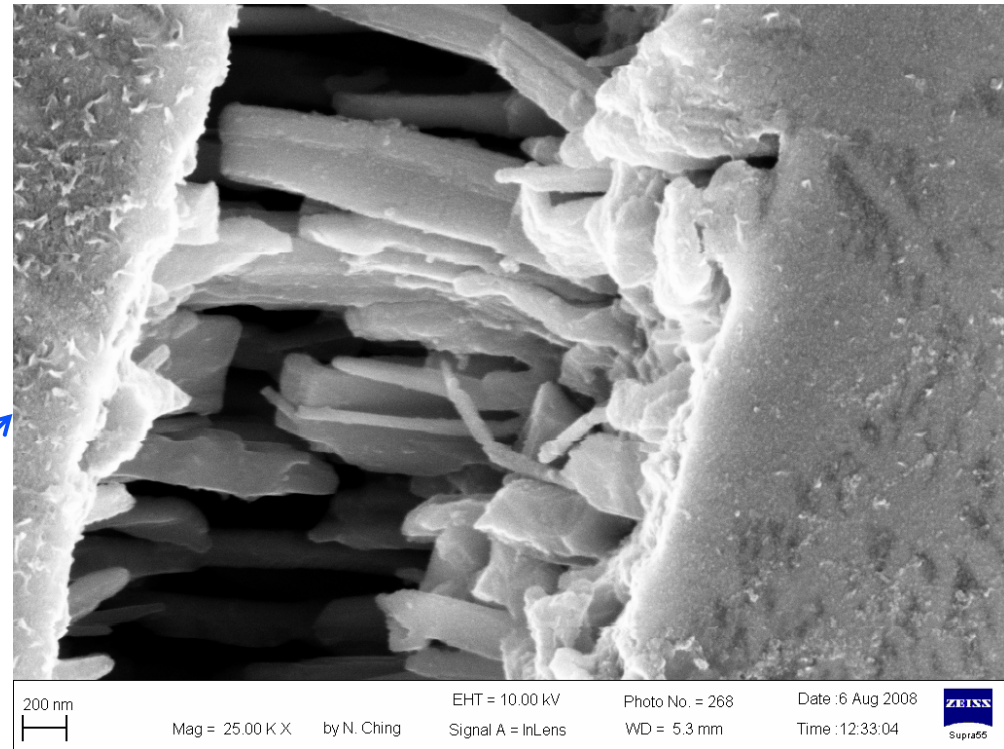
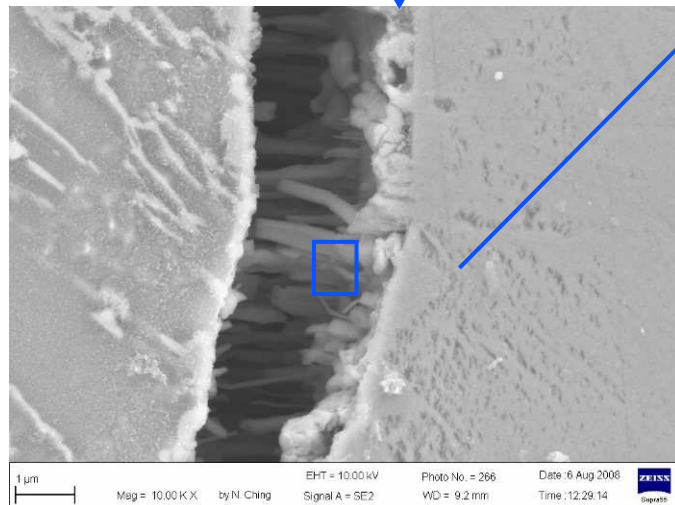
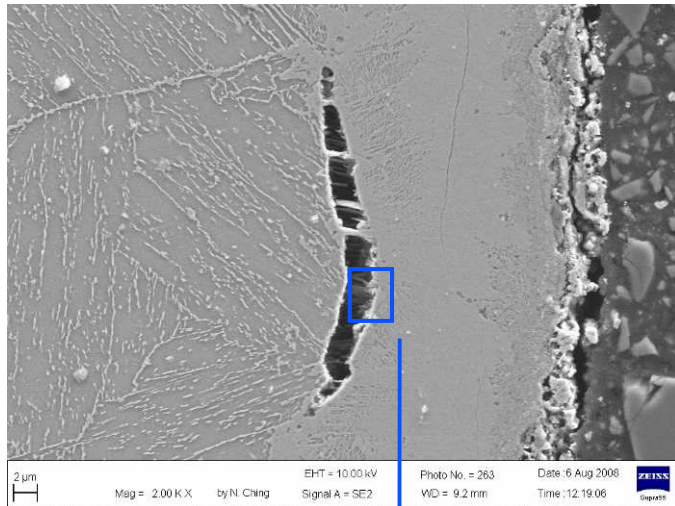
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Polished metallographic sample exhibiting DIGS.
The degree of porosity and the type scaffolding structure remaining inside each DIGS varies and at times appears as a nanostructure.

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- **What happened to the SARJ “as-designed” lubrication system?**
 - The sole lubrication between trundle rollers and the nitrided race ring was 1500-2000Å of gold deposited on the 440C rollers by ion plating.
 - Ground testing (in retrospect, inadequate and misleading) indicated that this lubrication design was sufficient to protect the nitrided 15-5PH steel race ring surface.
 - In addition, the ground environment was undermining the lubrication system by deteriorating the plating adhesion (see the following charts).
 - Once the transfer-film lubricant was lost, the kinematics of the SARJ mechanism coupled with very high friction coefficients pulled subsurface stresses up into the nitride layer, resulting in nitride layer fractures and loss of the nitrided surface.

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Carbon Tape Adhesion
Post-Test

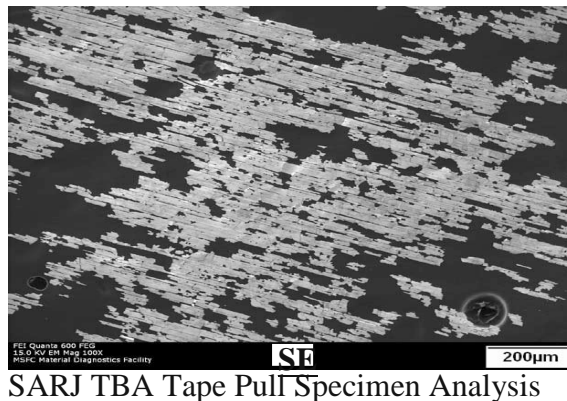
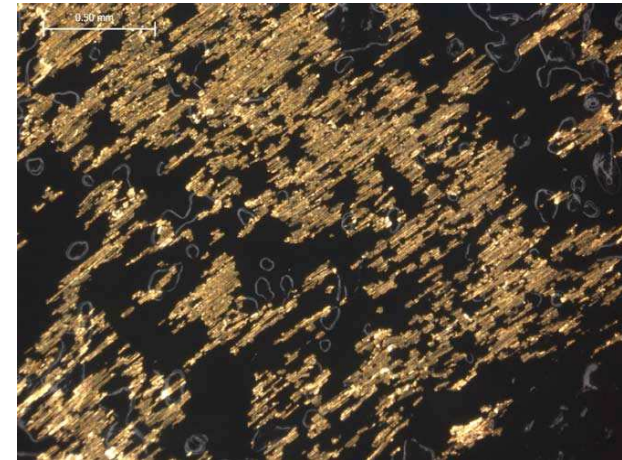


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TBA 1045, Datum A, Test #2, Carbon Tape



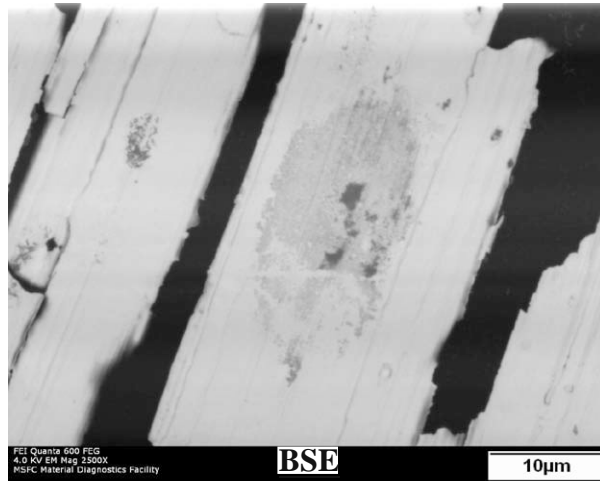
- Gold coating was easily removed from trundle bearing roller surfaces using carbon tape, and was generally segmented into strips of dimension consistent with the as-machined surface finish.

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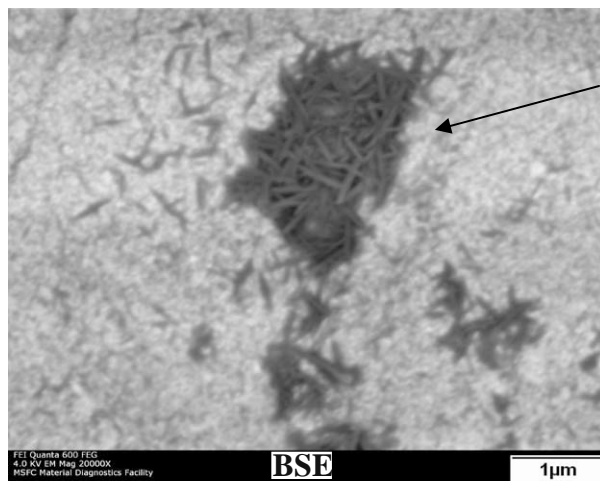
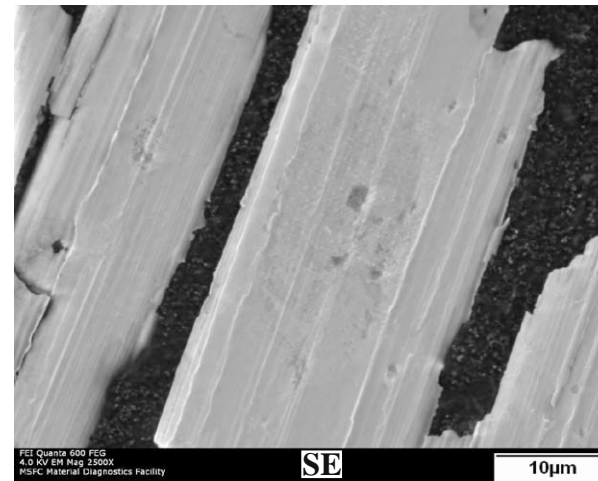
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TBA 1005, Outer 45, Test #1, SEM

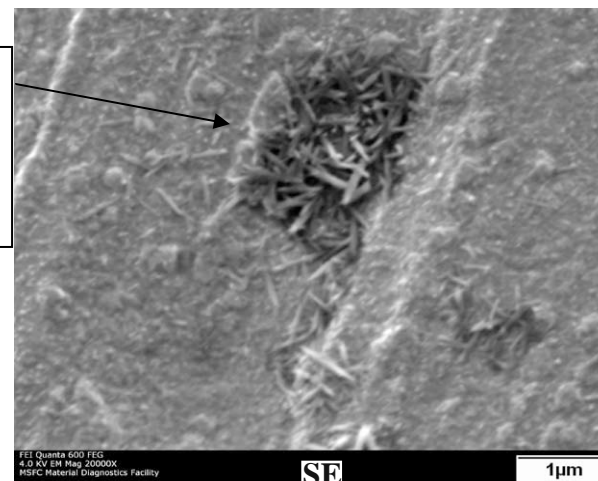


Outer
Surfaces



Iron Oxide
(by
elemental
analysis)

Inner
Surfaces

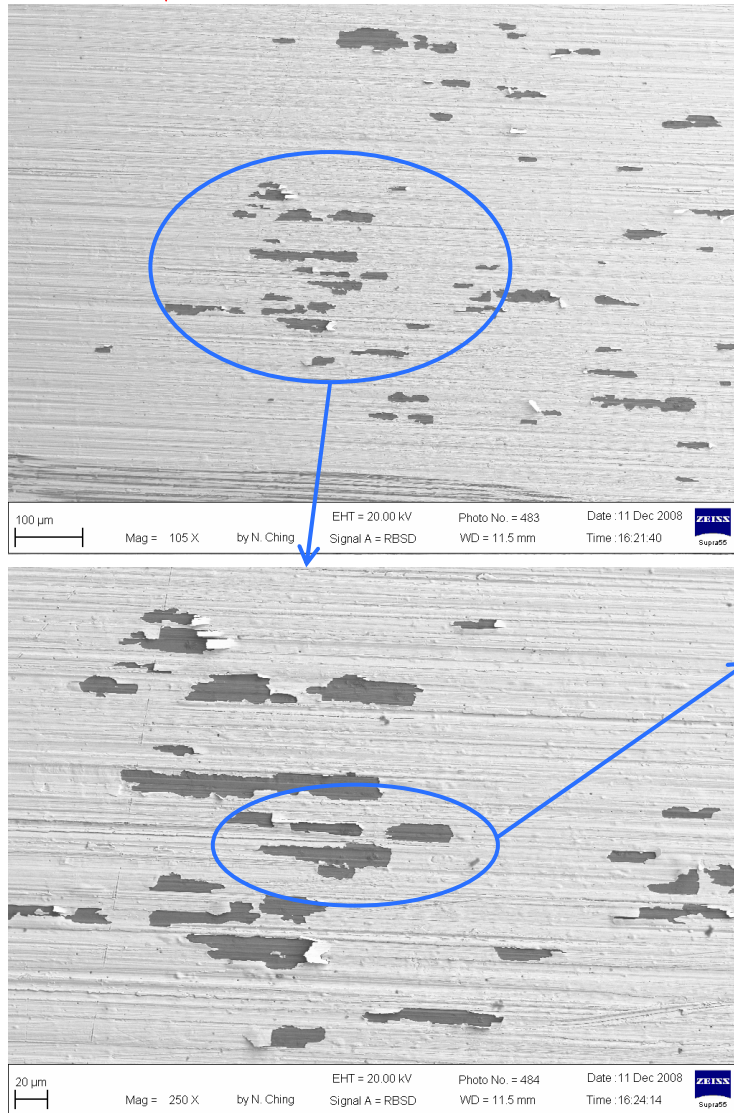


Prelim SARJ TBA Tape Pull Specimen Analysis

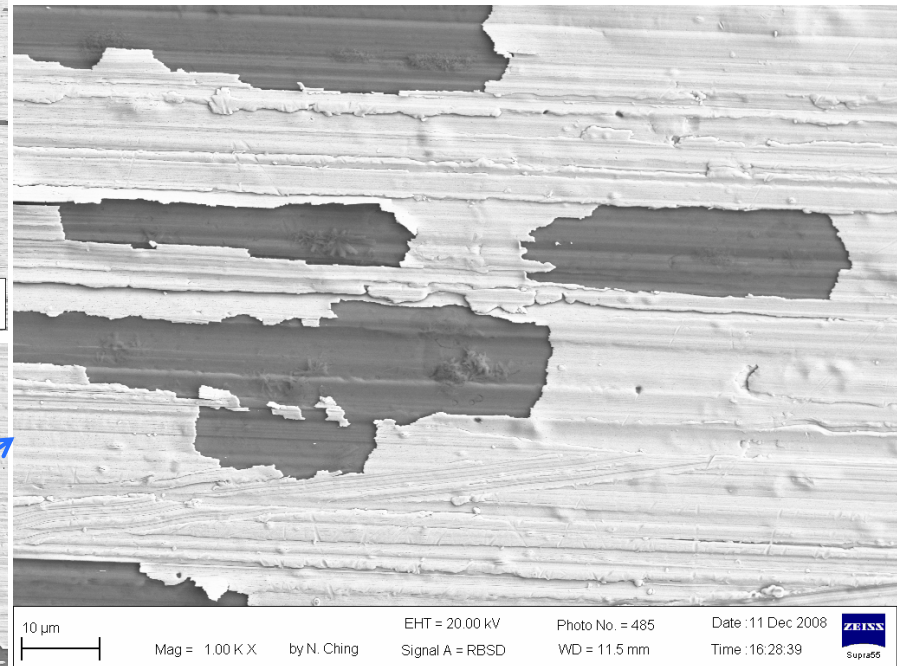
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➤ Freshly gold-plated 440C after 21 days of 95%RH at 125°F.



➤ Adhesion failure mode is consistent with that observed with trundle bearing rollers.

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- **Summary of Failure Analysis**

- The nitride surface of the SARJ race rings had unrecognized subsurface flaws susceptible to fracture initiation.
- The lubrication system selected in design was not robust enough to maintain friction control.
- Once friction control was lost, subsurface loads moved up into the interface of and within the nitride layer.
- Spalling probably initiated at DIGS, generating particles which exacerbated the surface stresses, leading to spalling of the nitride layer in a short period of time.
- Weak magnetic forces in the microgravity environment held released particles within in the mechanism, leading to crushing of the larger “chip” particles into fines and eventual agglomeration of those fines.

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- **What has happened to the SARJ mechanisms?**
 - We decided to lubricate using a MoS₂ + PTFE filled vacuum-stable grease.
 - We cleaned the damaged Starboard race ring using the same grease to help capture particulate.
 - We replaced all of the Starboard SARJ trundle bearing assemblies.
 - After several test runs of increasing duration plus analyses to determine the structural viability of the damaged race ring, the Starboard SARJ returned to nominal operation early 2010.
 - Performance is characterized as excellent.
 - We applied the same grease to the Port SARJ as soon as we could, and believe that we saved it from the same eventual failure mode.

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